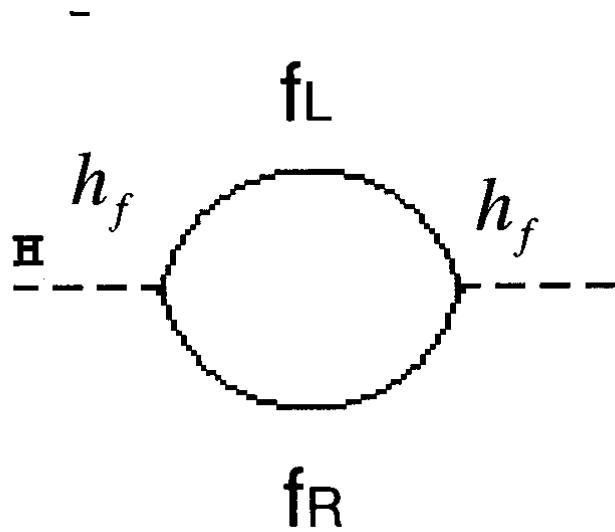


Vector Like Quarks

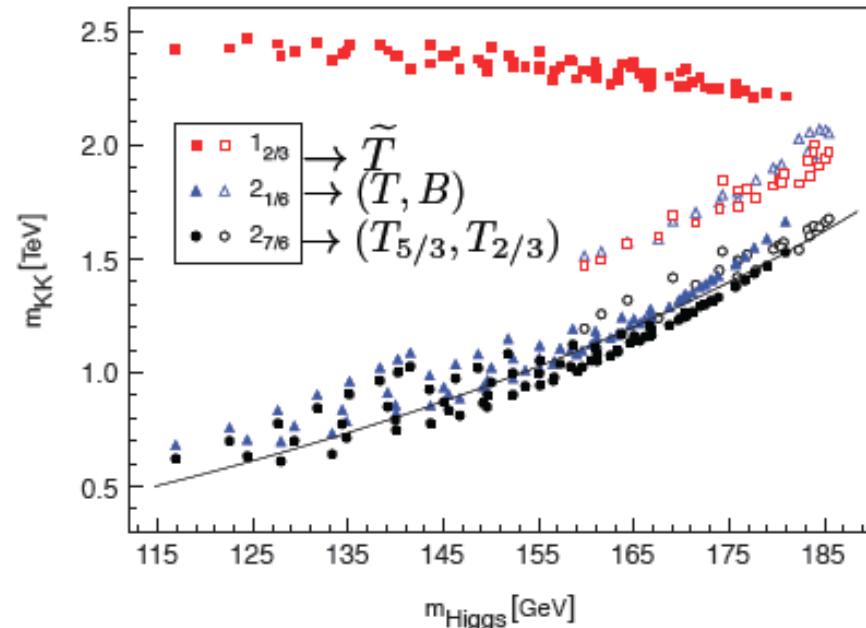
Kevin Black (Boston University)

Tim Andeen (Columbia), Aram Avetisian (BU), Tulika Bose(BU), Clare Bernard (BU), Mark Cooke (LBNL), Meenakshi Narain(Brown), Erich Varnes (Arizona), Natascia Vignaroli (MSU), Saptaparna Bhattacharya (Brown), Richard Nally (Brown) , Adam Scherlis (Brown) +??

Why top partners?



SUSY \rightarrow cancelation of top loop



MCHM

- At least one top partner below 1 TeV

Pomarol & Rivam 1206.6424
Contino, Da Rold, Pomarol' 06
[material from Servant, Anjou' 12]

4th Generation extension to SM

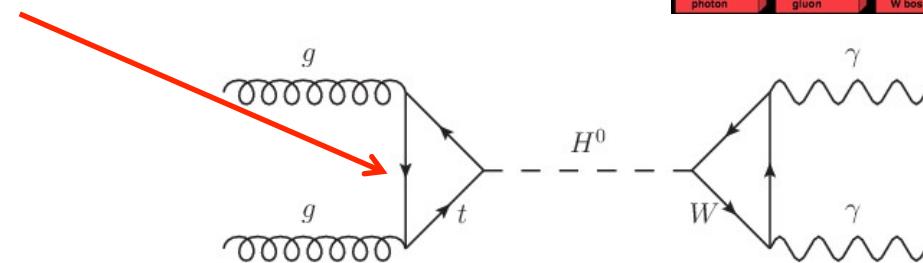
- A fourth **chiral generation** implies another $SU(2)_L$ doublet of quarks and the corresponding right-handed singlets
- So gluon fusion production would be enhanced by a factor of 9 – not supported by SM higgs only picture
- Unclear picture in more complicate Higgs sector

$$\begin{pmatrix} t'_L \\ b'_L \end{pmatrix} \quad t'_R, b'_R$$

$$g\bar{\psi}_L\phi\psi_R \rightarrow m\bar{\psi}_L\psi_R$$

EWSB

2.4 MeV/c ² 2/3 1/2 u up	1.27 GeV/c ² 2/3 1/2 c charm	172.5 GeV/c ² 2/3 1/2 t top	? ?/ t' ?
4.8 MeV/c ² -1/3 1/2 d up	104 MeV/c ² -1/3 1/2 s strange	4.2 GeV/c ² -1/3 1/2 b bottom	? ?-1/3 1/2 b' ?
< 2.2 eV/c ² 0 1/2 e electron neutrino	< 17 MeV/c ² 0 1/2 ν_μ muon neutrino	< 15.5 MeV/c ² 0 1/2 ν_τ tau neutrino	? 0 1/2 ν₄ ?
0.511 MeV/c ² -1 1/2 e electron	105.7 MeV/c ² -1 1/2 μ muon	1.777 GeV/c ² -1 1/2 τ tau	? -1 1/2 l₄ ?
0 0 1 γ photon	0 0 1 g gluon	80.4 GeV/c ² ± 1 W [±] W boson	91.2 GeV/c ² 0 1 Z ⁰ Z boson



Why are they called vector like?

- A SM chiral quark couples only to the left-handed charged current (V-A) interaction
- Vector like quarks would couple to both the left handed and right-handed charged current

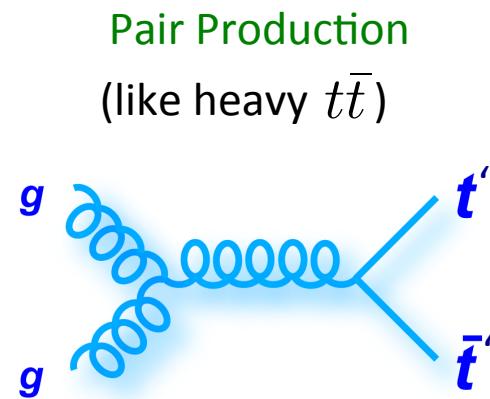
$$\begin{aligned} J_L^{\mu+} &= \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = \textcolor{red}{V} - \textcolor{blue}{A} \\ J_R^{\mu+} &= 0 \end{aligned}$$

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d = \textcolor{red}{V}$$

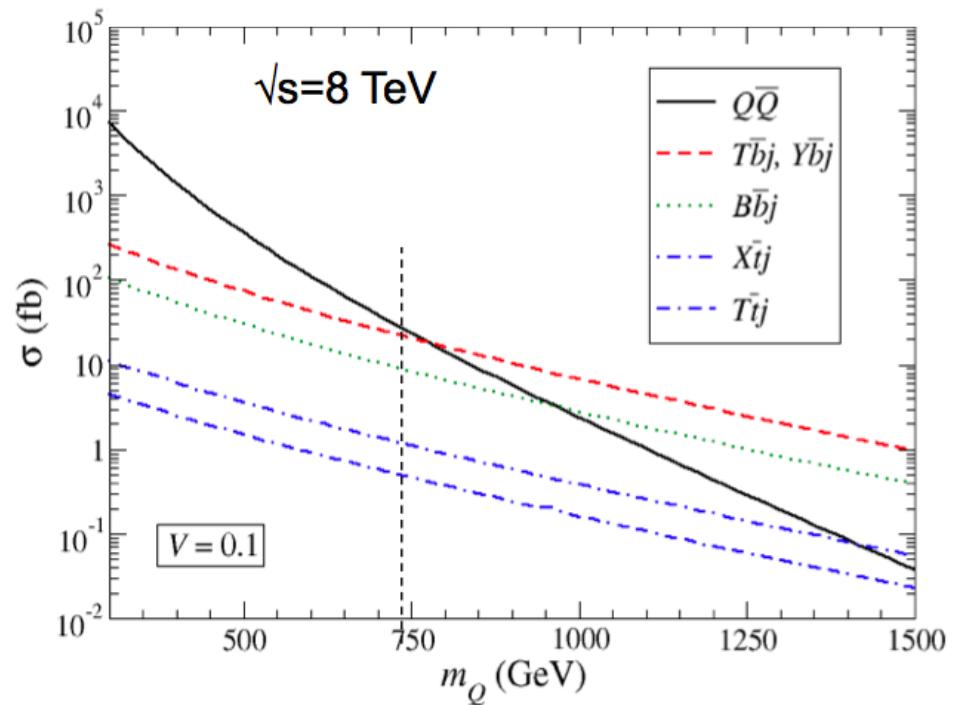
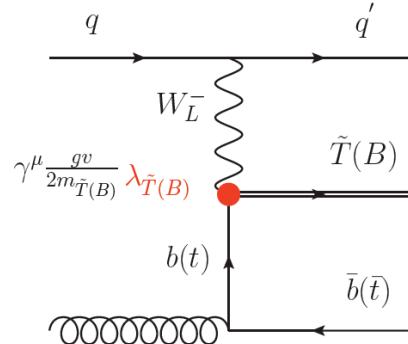
Production

- New quarks can be produced singly or in pairs at the LHC.

J.A. Aguilar-Saavedra (priv. com. , c.f. JHEP 11, 030 (2009))



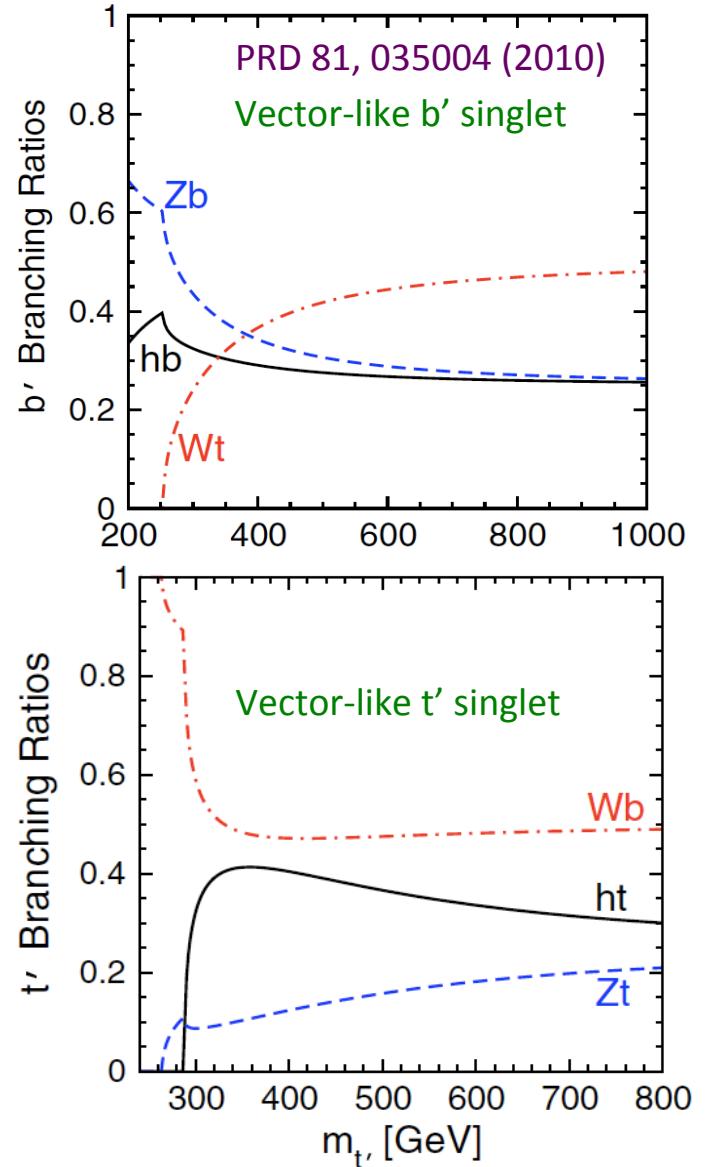
Single Production
(depends on charge, coupling)



- **Vector-like:** left and right handed component quantum numbers are the same, e.g. :

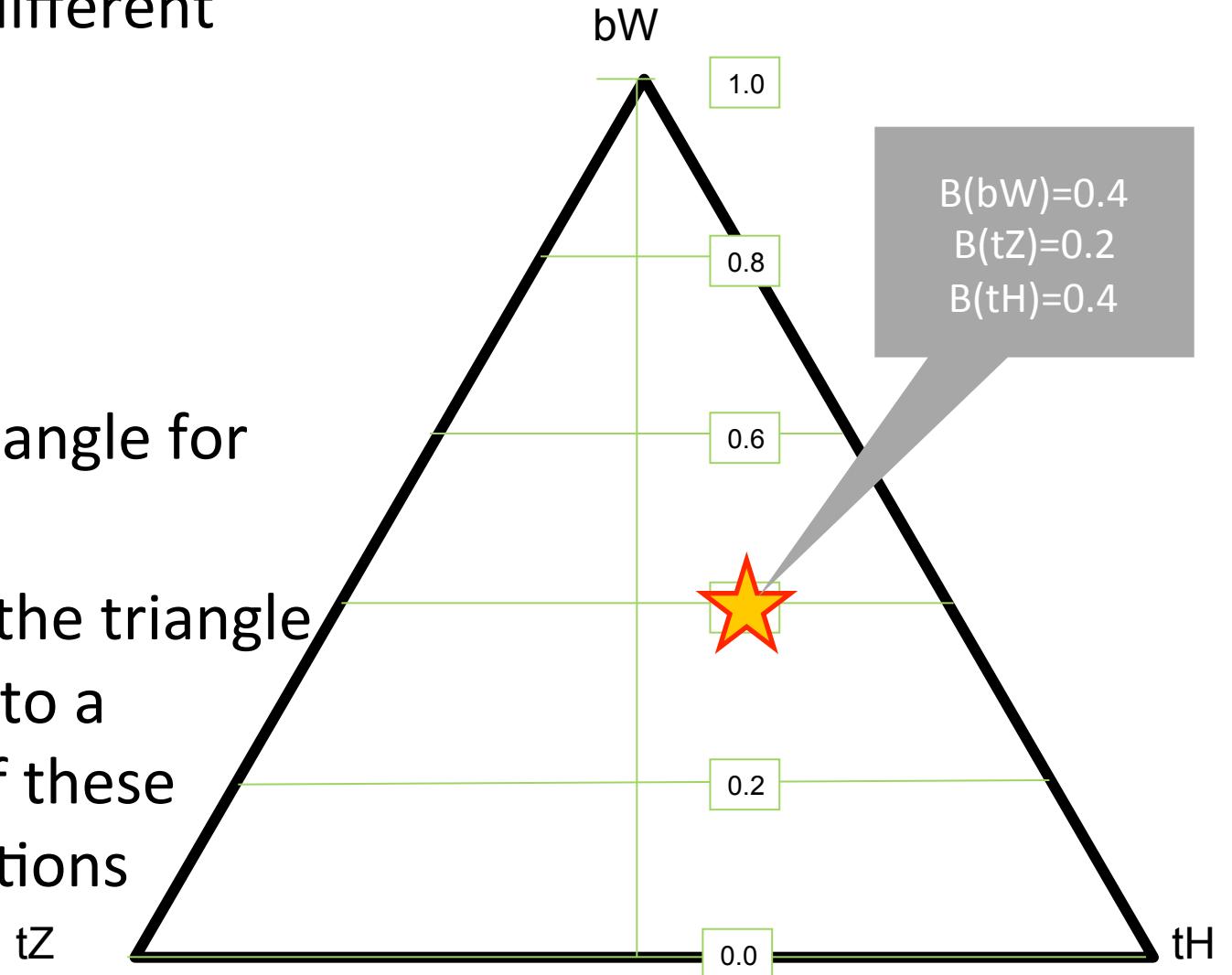
Vector-like singlets	t'_L	t'_R
Vector-like doublets	$\begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$	$\begin{pmatrix} t'_R \\ b'_R \end{pmatrix}$

- Gauge invariant mass term independent of the SM Higgs $M\bar{\psi}_L\psi_R$
- Mixing of weak eigenstates w/ different isospin breaks GIM and induces tree level FCNC.
- Mixing with 3rd generation generally preferred in most models (though caveats exist), and is experimentally less well constrained.
- Present in many BSM models: Little Higgs, Composite Top/Higgs, Extra Dims., GUTs, extended SUSY, ...



Recasting to a Triangle

- T decays into different final states
 - $T \rightarrow bW$
 - $T \rightarrow tZ$
 - $T \rightarrow tH$
- there is one triangle for every T mass
- every point in the triangle corresponds to a different set of these branching fractions



Large Number of Final States!

H->bb

Channel	Multi-leptons	Lepton+jets
tHWb	$2l(\text{OS})+\text{MET}+4b$	$l+\text{MET}+2j+4b$
tH tZ ($Z \rightarrow jj(bb)$)	$2l+\text{MET}+2j+4b$	$l+\text{MET}+4j+4b$
tH tZ ($Z \rightarrow \nu\nu$)	$2l+\text{MET}+4b$	$l+2j+\text{MET}+4b$
tH tZ ($Z \rightarrow ll$)	$4l+\text{MET}+4b$ or $3l+\text{MET}+2j+4b$	
tZ tZ ($ZZ \rightarrow jj(bb)$)	$2l(\text{OS})+\text{MET}+2j+2b$	$l+\text{MET}+4j+2bz$
tZ tZ ($ZZ \rightarrow \nu\nu$)	$2l(\text{OS})+\text{MET}+2b$	$l+2j+\text{MET}+2b$
tZ tZ ($ZZ \rightarrow ll$)	$4l+\text{MET}+2b$ or $3l+2j+\text{MET}+2b$	
tHtH ($H \rightarrow bb$)	$2l(\text{OS})+\text{MET}+6b$	$l+\text{MET}+2j+6b$
WbWb	$2l(\text{OS})+\text{MET}+2b$	$l+\text{MET}+2j+2b$
WbtZ ($Z \rightarrow jj(bb)$)	$2l+\text{MET}+2j+2b$	$l+\text{MET}+4j+2b$
WbtZ ($Z \rightarrow \nu\nu$)	$2l+\text{MET}+2b$	$l+\text{MET}+2j+2b$
WbtZ ($Z \rightarrow ll$)	$4l+\text{MET}+2b$ or $3l+\text{MET}+2j+2b$	

Large number of Final States!

H->WW

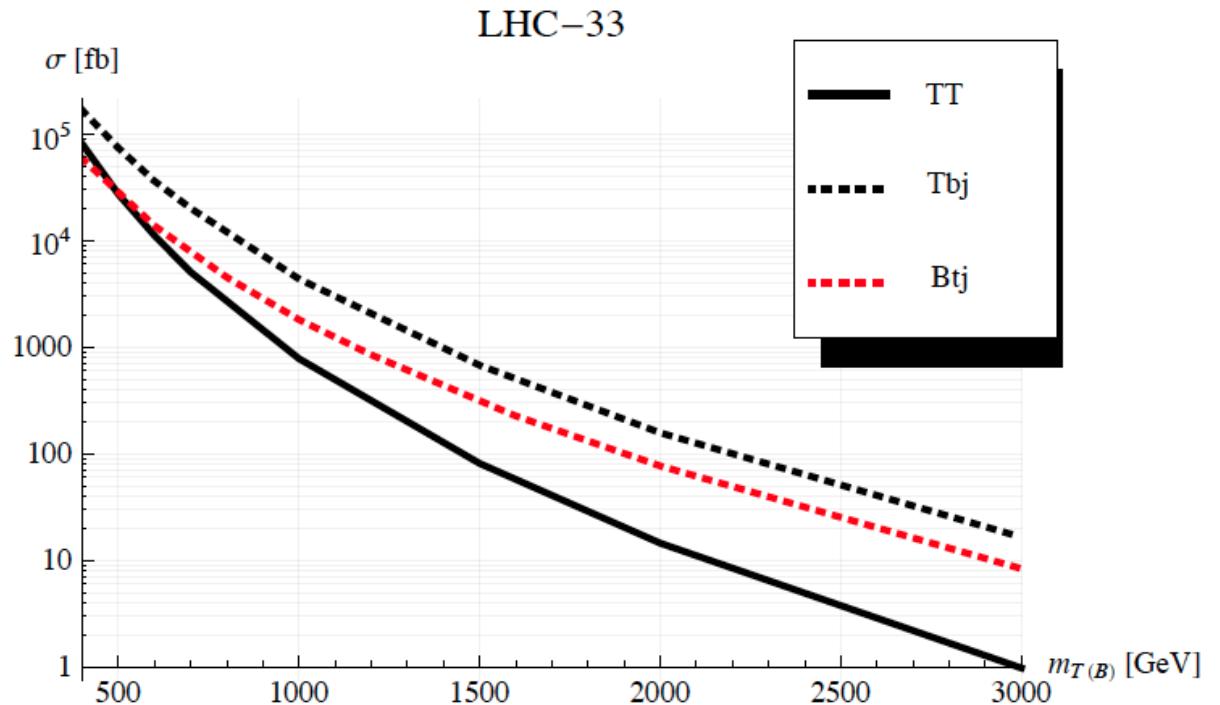
-

Channel	Multi-leptons	Lepton+jets
tHWb	$4l + \text{MET} + 2b$ or $2l(\text{SS}) + \text{MET} + 4j + 2b$	$l + \text{MET} + 6j + 2b$
tH tZ ($Z \rightarrow jj(bb)$)	$4l + \text{MET} + 2j + 2b$ or $2l(\text{SS}) + \text{MET} + 6j + 2b$	$l + \text{MET} + 8j + 2b$
tH tZ ($Z \rightarrow \nu\nu$)	$4l + \text{MET} + 2b$ or $2l(\text{SS}) + \text{MET} + 4j + 2b$	$l + \text{MET} + 6j + 2b$
tH tZ ($Z \rightarrow ll$)	$6l + \text{MET} + 2b$ or $3l + \text{MET} + 6j + 2b$	
tHtH ($H \rightarrow W^+W^-$)	$6l + \text{MET} + 2b$ or $3l + \text{MET} + 6j + 2b$	$l + \text{MET} + 10j + 2b$
tHtH ($H \rightarrow W^+W^-, b\bar{b}$)	$4l + \text{MET} + 4b$ or $2l(\text{SS}) + \text{MET} + 4j + 4b$	$l + \text{MET} + 6j + 4b$

Cross-Sections

- Preliminary cross-sections
for single and pair produced
Vector-quarks
- pair production (pure QCD)
 - single production depends on
EW properties (more model
dependent)
 - Pair production ~20% higher
@NLO

Natascia Vignaroli (MSU) @LO



S. Bhattacharya (Brown)

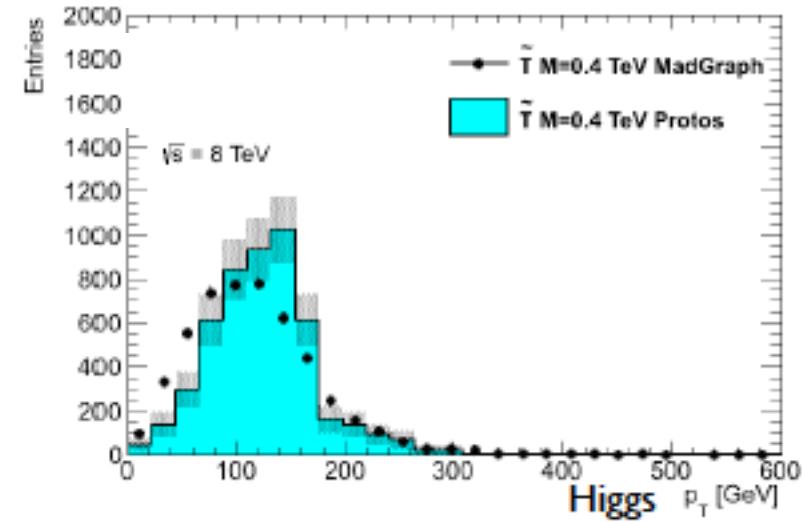
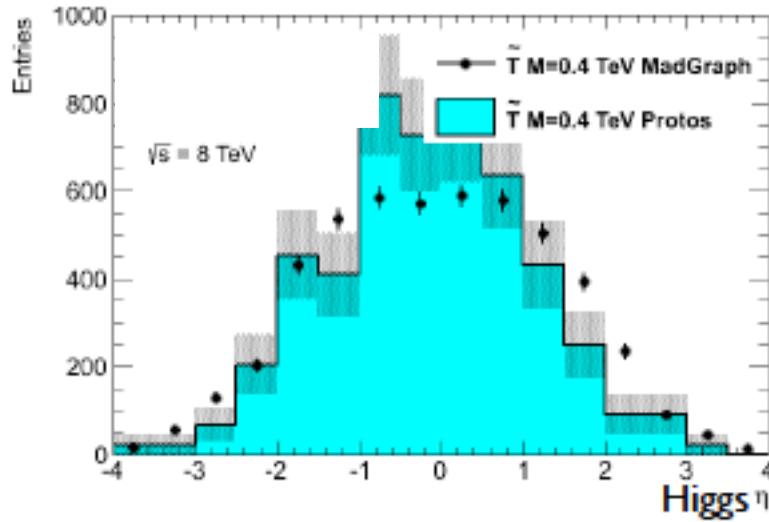
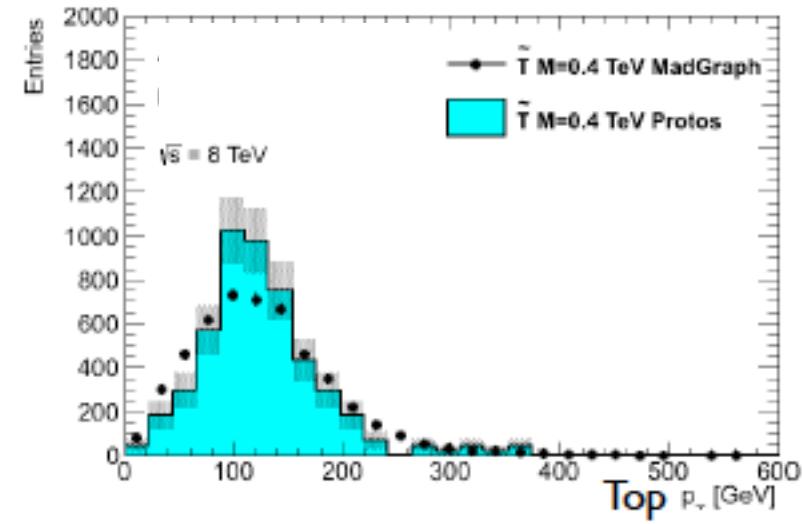
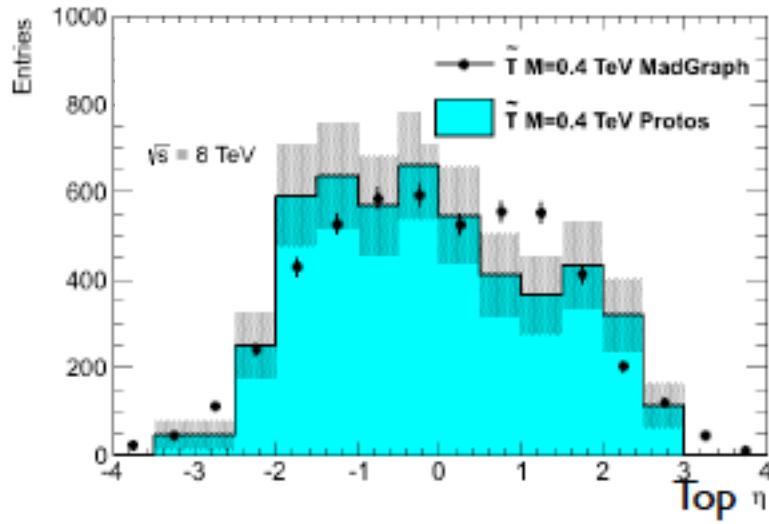
Event Generation

- Look at two different implementations (Protos and Madgraph)
- 400 GeV single T production
- Note that adjustable parameters are somewhat different (notably width in madgraph is directly adjustable while in Protos it is fixed by other adjustable parameters (mixing and allowed decays))

$$(\tilde{T} \rightarrow (h \rightarrow bb)t)b + X$$

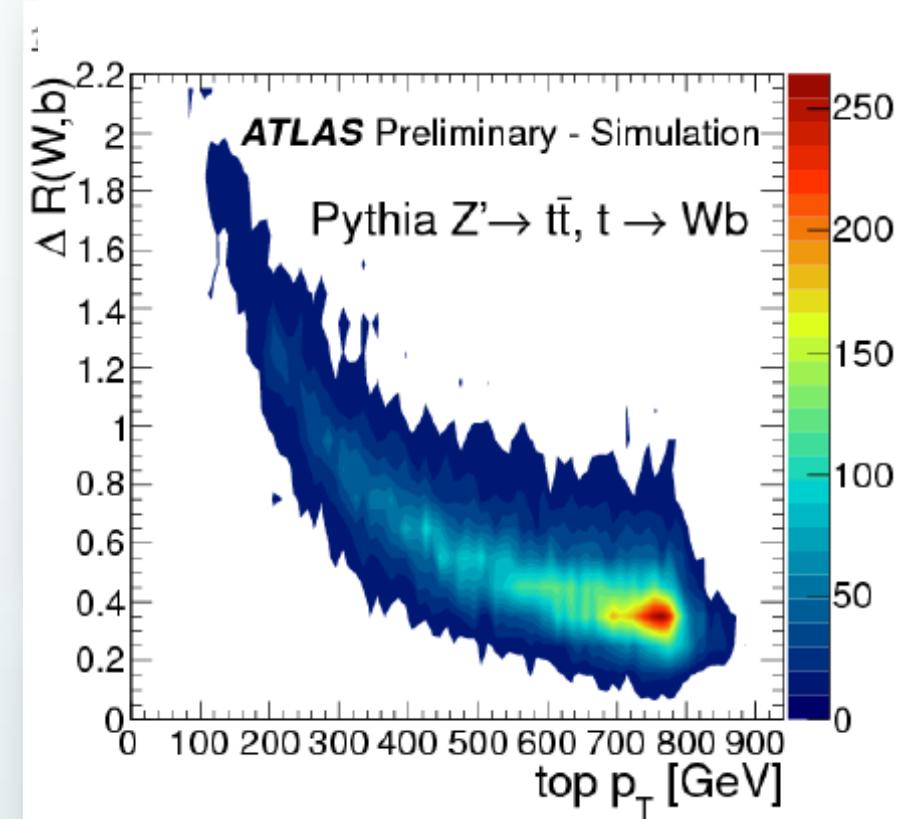
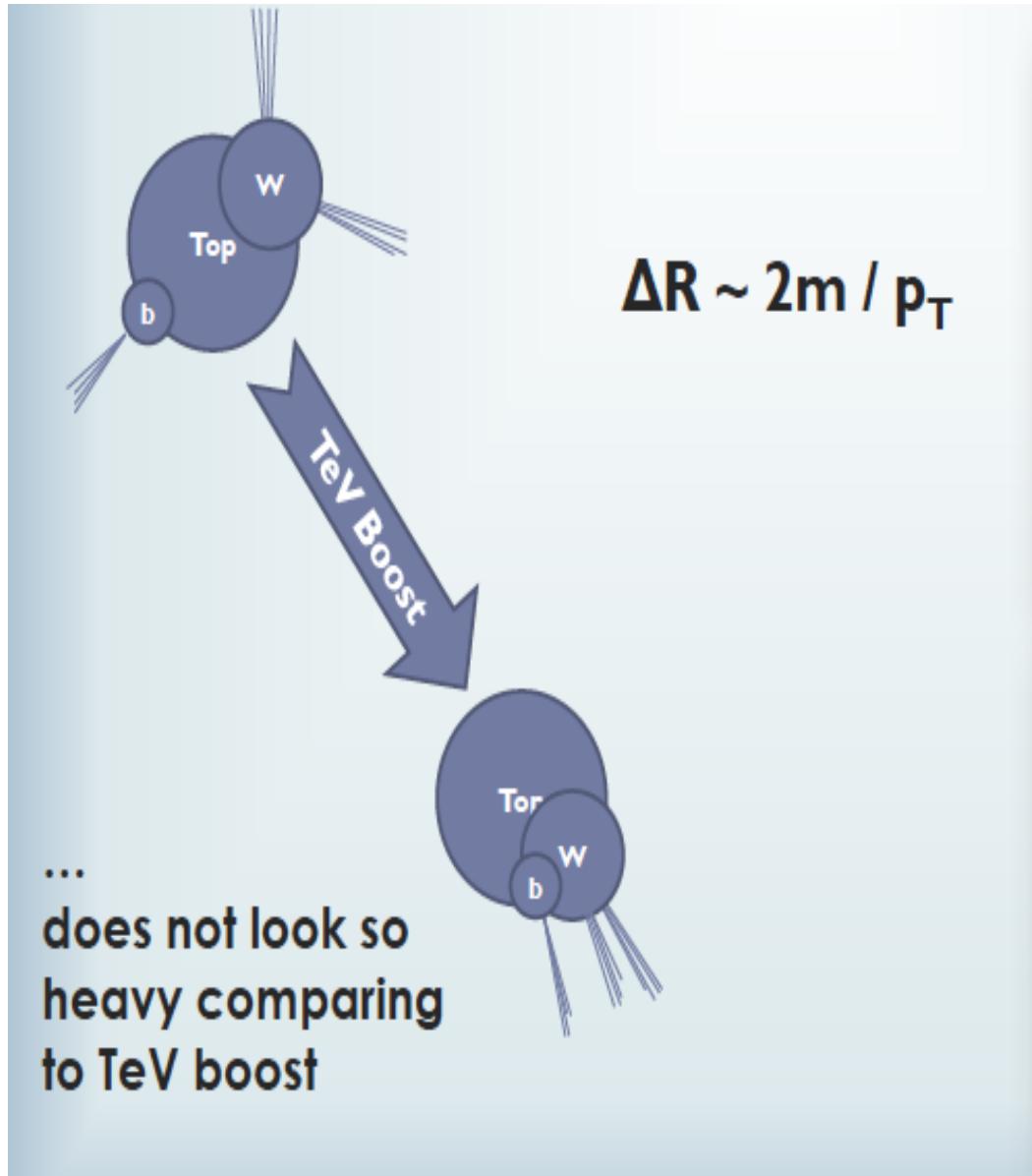
Too many channels to do them all
Started looking in lepton+jets final state

Generator Level Plots



Tim Andeen (Columbia)

Issues to watch for – boosted objects



For lower mass, not an issue but for Very heavy ones starts to become An issue

Conclusions

- Investigate sensitivity to vector like quarks
 - “Natural” light partner on the order of \sim TeV, but investigate sensitivity
 - Particular issue is dealing with boosted objects (jets but also leptons for high enough boost!)
- What can we say about properties
 - Spin, charge, ...